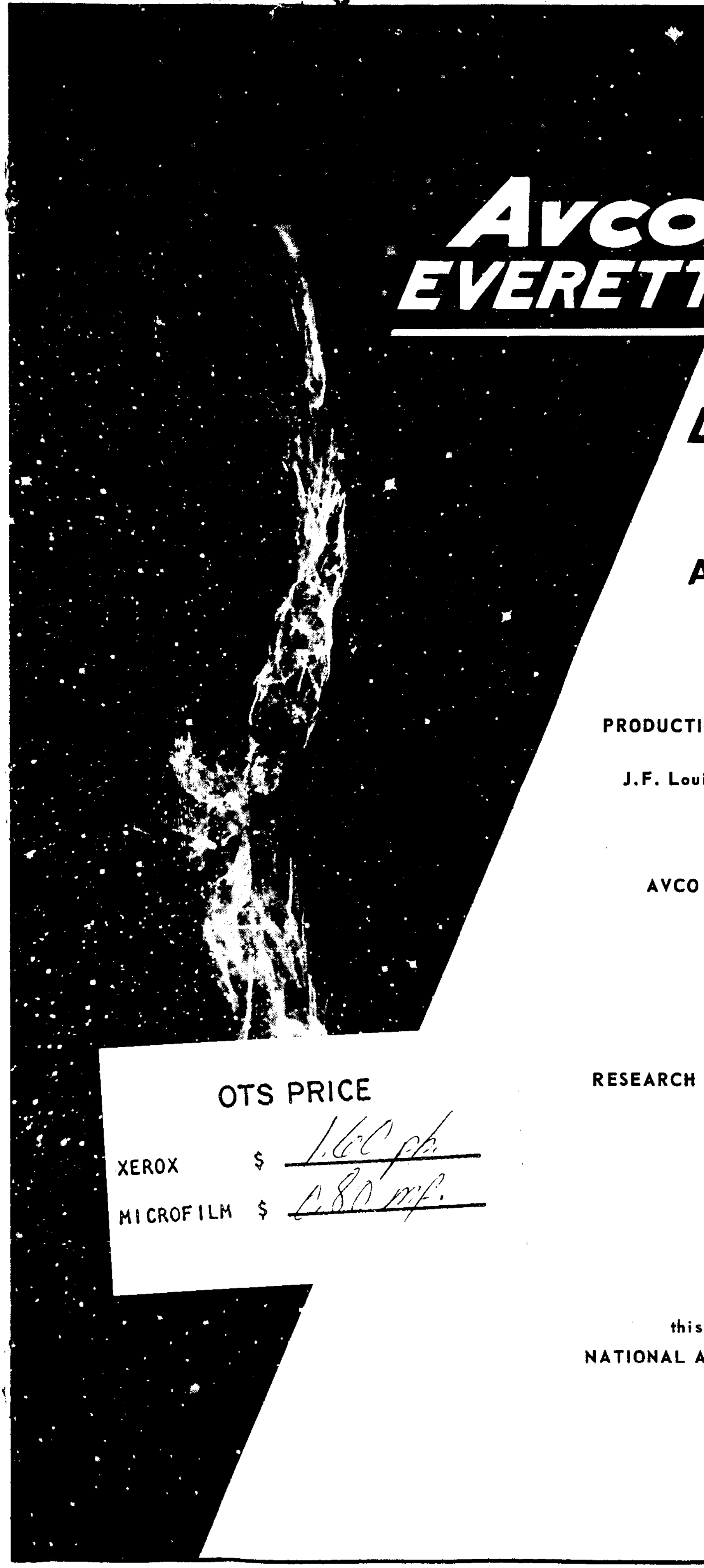

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PRODUCTION OF INTENSE RADIATION HEAT PULSES

J.F. Louis, R. Decher, R.A. Allen, and T.R. Brogan

prepared by

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RESEARCH AND ADVANCED DEVELOPMENT DIVISION
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Wilmington, Massachusetts

AMP 120
September 1963

this work has been partially supported by
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ABSTRACT

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At the re-entry velocities typical of interplanetary flights, it is likely that very high heat transfer rates to the entering vehicle will be encountered due to radiation from the hot gases surrounding the body. These rates can approach 50 KW/cm^2 in some cases.

An experimental setup has been developed for the production of intense radiation heat pulses which can be used to simulate the very high heat transfer rates due to radiation from the hot gases surrounding bodies at re-entry velocities typical of interplanetary flights. Radiation heat transfer rates up to 51 KW/cm^2 were determined at pressures up to four atmospheres absolute. The effective temperature of the gas column was determined by several methods and the results concur. A theoretical calculation of the radiation heat transfer agrees closely with the experimental result, and it is also found that the aerodynamic heat transfer is much smaller. Different materials were tested in this experimental setup and the high values obtained for the heat of ablation indicate an important shielding of the material by the vaporized matter between the wall and the arc column. More work remains to be done to understand the detailed mechanism of heat transfer, and to relate the results to actual flight situations. Author

At the re-entry velocities typical of interplanetary flights, it is likely that very high heat transfer rates to the entering vehicle will be encountered due to radiation from the hot gases surrounding the body.[1,2] These rates can approach 50 KW/cm^2 in some cases. In order to study the behavior of protective materials for this environment, it is desirable that steady state simulation of the conditions be provided in the Laboratory. This work has been directed to this simulation. Under the program, a method of producing intense radiation heating has been developed, and materials have been subjected to radiative heat pulses at varying levels up to 51 KW/cm^2 (45,000 BTU/ft^2 sec) and at ambient pressures up to four atmospheres absolute. Values for heats of ablation (Q^*) have been obtained. More work is required to fully understand the results and, in particular, to relate them directly to the flight situation.

Figure 1 (a) is a schematic diagram of the facility which has been developed. It consists of a high powered arc surrounded by the material to be tested. A cylindrical hole is bored through the test sample and the electrodes are located at its ends as shown. When the arc is struck, the discharge column fills most of the volume of the hole. The total power into the arc is equal to the product of the current, I, by the arc voltage V. With the enclosed arc configuration, there are three ways the power can be dissipated:

1) Electrode losses
2) Absorption by the test material (heating, melting, vaporization)
3) Superheating of material vaporized from the test specimen (and electrodes)

In actual operation, the arc burns in the vaporized material ablated from the test specimen and the graphite electrodes. The pressure in the arc column rises above the ambient pressure, and the superheated ablated material is discharged through the passage between the electrodes and the test material.

The pressure is determined by the rate of material vaporization, the temperature of the arc, and the size of the clearance between the electrodes and the test sample. In the center of the test specimen, aerodynamic stagnation conditions prevail as shown and the joule heat dissipated in the center of the arc column falls onto the boundary, i.e., low temperature vaporized material and the wall. The streamlines shown in Fig. 1 (a) indicate that convection of ablated material plays an important role on the heat actually transferred to the test specimen. In this respect, the simulation strongly resembles the flight situation where the combination of radiation from the hot gas through the ablated material to the body, absorption of this radiation in the cooler gas near the body, and the aerodynamic convection, through its influence on the thickness of the ablation layer, will determine the heat absorbing capacity of the material.

During a test, the total current, I, is measured as well as the local electric field, E, along the wall using the probes shown in Fig. 1 (a). Thus, the local power dissipated in the arc column is determined by the product of the current density by the local electric field found from the probe voltages. Therefore, the average heat transfer rate $\dot{q}$, falling onto the test specimen can be determined for the center of the test section where stagnation conditions prevail. In the usual manner, the effective heat of ablation, Q^*, is then equal to the ratio of the apparent heat transfer rate to the mass rate of ablation per unit area.

Two versions of the arc powered simulator have been built to date. A 3.3 megawatt battery bank was conveniently available as a power supply for the tests. The first facility operated at a total power of up to 3 MW and at currents up to 22,000 amperes for 3 seconds, and once was operated for one minute at 500 KW input. The time limitation is basically due to gross changes in test specimen dimension after times dependent on the nature of the test material and the power input. A transite pipe with a viewing window surrounds the arc. At the end of the run, nitrogen was injected about the specimen to quench any spontaneous combustion of the graphite electrodes and test material. But this was not completely effective, as the nitrogen entrained some air. Therefore, a second version with a sealed test section where the material would remain in a nitrogen atmosphere after shutdown was built. Figure 1 (b) is a diagram of the second facility. This second facility has basically the same configuration and capability as the first except for its internal atmosphere control.

As mentioned above and shown in Fig. 1 (a), the current and the voltage distribution throughout the sample are measured to determine the power density. For electrically insulating test materials, voltage probes are introduced in the sample. In the case of electrically conducting materials such as graphite, the test section is made of thin washers coated with a thin layer of arc sprayed alumina to provide the insulation. Voltage taps can be made on the washers and power density determined. Pressure measurements have been carried out using a Kistler gauge. Figure 2 shows the first facility in operation with the high temperature ablated material streaming out through the clearance between the electrodes and the test's specimen.

Preliminary tests were carried out on maple wood, Refrasil reinforced phenolic, bonded graphite cloth, graphite, and teflon. Table I summarizes these results, giving the total power, the heat transfer rate, and the heat of ablation.

TABLE I

Materials	Arc Power Input KW	σ mho/cm	$\dot{q}$ KW/cm^2	Q* cal/g	Q* Btu/lb
Refrasil Reinforced Phenolic	2860	3600	51	17300	31400
" " "	324	3600	2.88	4400	8000
" " "	965	7160	8.3	6400	11620
" " "	2250	6480	18	7680	13900
" " "	3110	6800	22.6	6180	11250
Bonded Graphite Cloth	2860	3600	51	30000	54500
Maple Wood	2320	5100	33	7200	13100
Graphite	2225	3200	20.5	42400	77000
Teflon	2225	3200	20.5	8600	15650

Heat transfer rates up to 51 KW/cm^2 and heats of ablation up to 40,000 cal/g were recorded. After the test, the samples were cut and examined for change in dimensions. Figure 3 shows the condition of representative samples after test. Testing was carried out on linen phenolic at different pressures by changing both the power input and the clearance area. The results are plotted on Fig. 4 and show that the heat of ablation increases with the pressure up to 1.5 atm. At pressure higher than 1.5 atm the heat of ablation, Q^*, is essentially constant within the scatter of the data. Generally speaking, the measured heats of ablation are quite high, indicating an important shielding of the material due to the presence of vaporized absorbent material between the gas and the body, and/or to blowing.

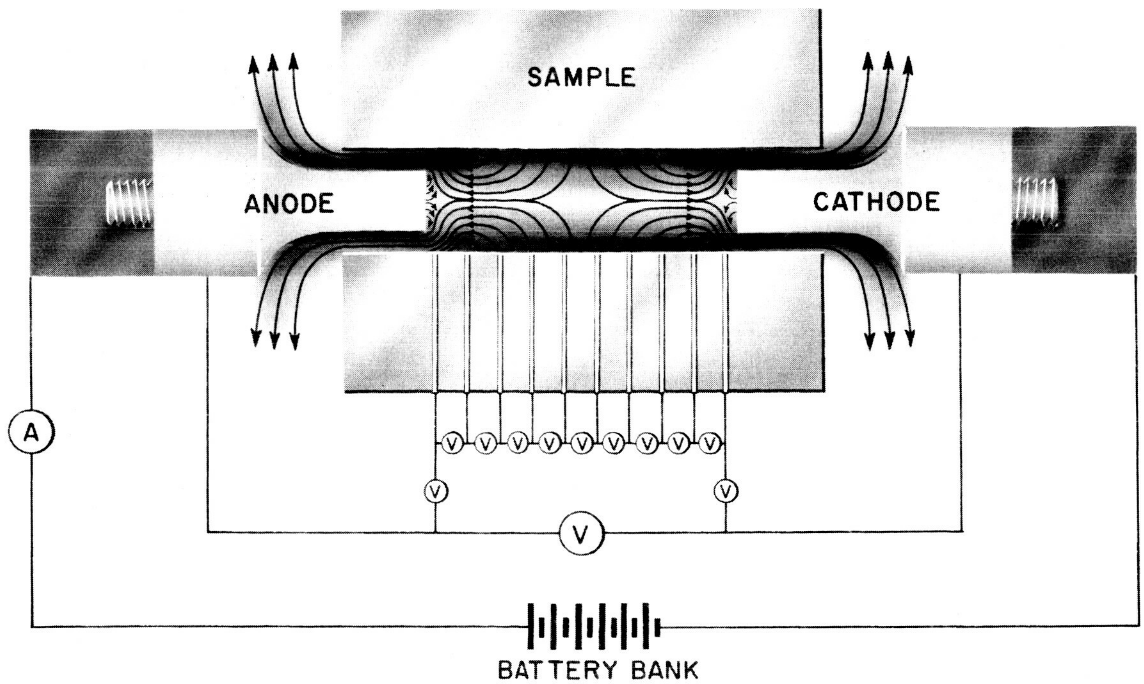
To date, diagnosis of the test results has been limited. The gas temperature in the arc column has been estimated in several ways with fair agreement. Using this estimated temperature, and theoretical studies of gas radiation, it is possible to estimate the radiation heat transfer from the hot arc gas. The heat transfer estimated in this manner is in fair agreement with that determined from the electric field-current measurements described previously.

Four methods have been used to estimate the temperature in the arc: (1) the effective electrical conductivity of the gas can be calculated from the electric field-current measurements assuming the arc fills the bore of the test specimen. Assuming that the ionization is due primarily to carbon vapor with an ionization potential much less than that of the other constituents of the sample, a temperature can be determined from the Saha equation using the measured arc pressure, (2) spectra of the arc column have been taken through windows in the sample. The electron concentration can be determined from the broadening of the hydrogen beta line.[3] From this electron density, a temperature can be estimated as described above. Since the spectrograph is focused on the center of the arc column, and looks through the thickness of the column, the measured temperature is an effective temperature for radiation, (3) comparison of the intensity of the H_α and H_β lines can be used to estimate an effective radiation temperature, (4) from the measurement of the mass rate of ablation and the pressure in the arc column, an average temperature can be calculated since the clearance area between the test sample and the electrodes is known. Temperatures determined using the above techniques were in fair agreement ($\pm$ 10%) and varied between 12,000°K and 18,000°K depending on the test conditions.

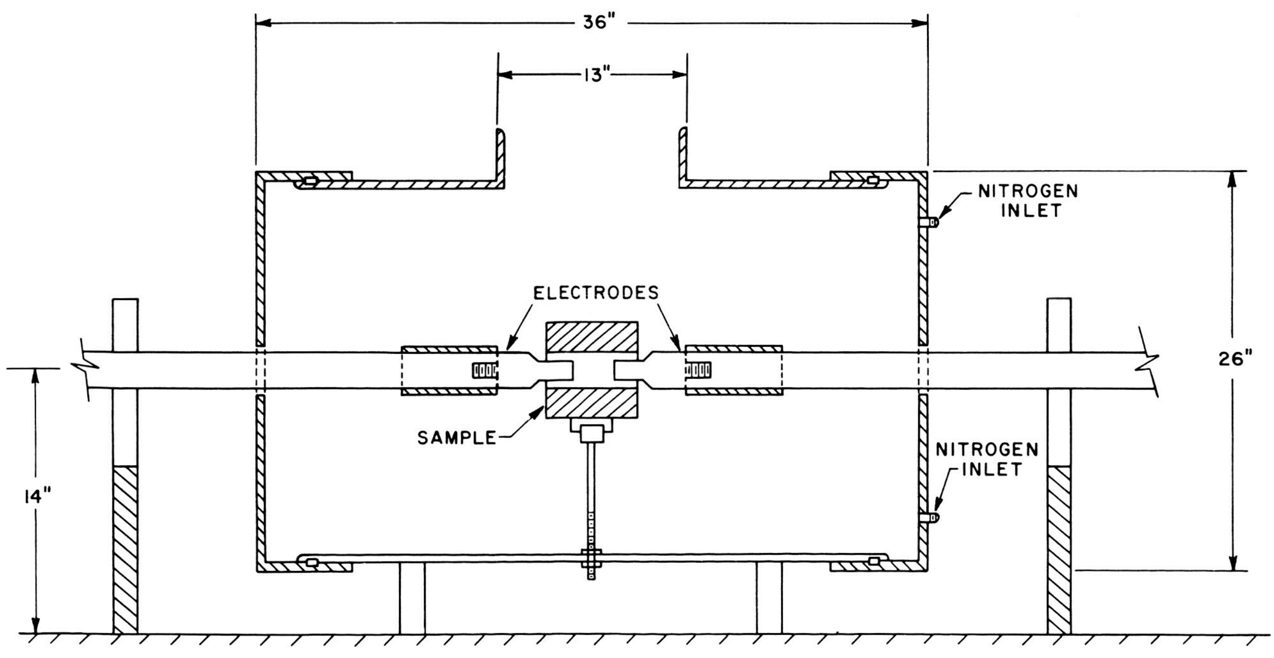
Figure 5 compares the spectra of an arc column in linen phenolic at pressures of 1.54 atm and 3.6 atm. Both spectra show the Stark broadening of the H lines and the absorption bands of CN and C_2. These molecules exist in the boundary, and the rate of decrease of intensity from the band's head indicates a temperature between 6000° and 1500°K. The Stark broadening of the H_β line indicates electron concentrations of 1.8 and 8.5 10^{17} electron/cm^3.

The continuum radiation from carbon vapor was determined for a gas temperature of 16,000°K (as determined from apparent gas conductivity) and a pressure of three atmospheres.[4,5] These conditions correspond to those of the first test listed in Table I where the arc power input was 2860 KW and the measured Q* 17,300 cal/gm. The continuum radiation calculation assuming an actual thickness equal to the arc diameter (3 cm) yielded a total radiation heat transfer rate of 44 kilowatts/cm^2 compared to 51 KW/cm^2 as determined from the electric field-current measurements. Thus, the experiment appears relatively self-consistent.

The velocity gradient at the stagnation point in the center of the arc column can be estimated from the effective arc temperature, pressure, and the ablation rate. The average gas enthalpy can be determined from the temperature estimate and the pressure so that the convective heat transfer in the stagnation region can be estimated.[6] Assuming that the specimen wall is at the boiling point of graphite ($\approx$ 4000°K) and for the same conditions for which the radiative transfer was compared with the electric field-current rate, a convective heat transfer of 2.6 KW/cm^2 is indicated. Thus, it appears that radiation is the primary heat transfer mechanism in the apparatus. Further, these results, together with the high Q* values such as those shown in Fig. 4 would indicate that body shielding due to absorption by ablated material of substantial optical thickness near the body can be very important.



a) Principle of operation of the radiation heat transfer facility



b) Sketch of the second facility

Figure 1

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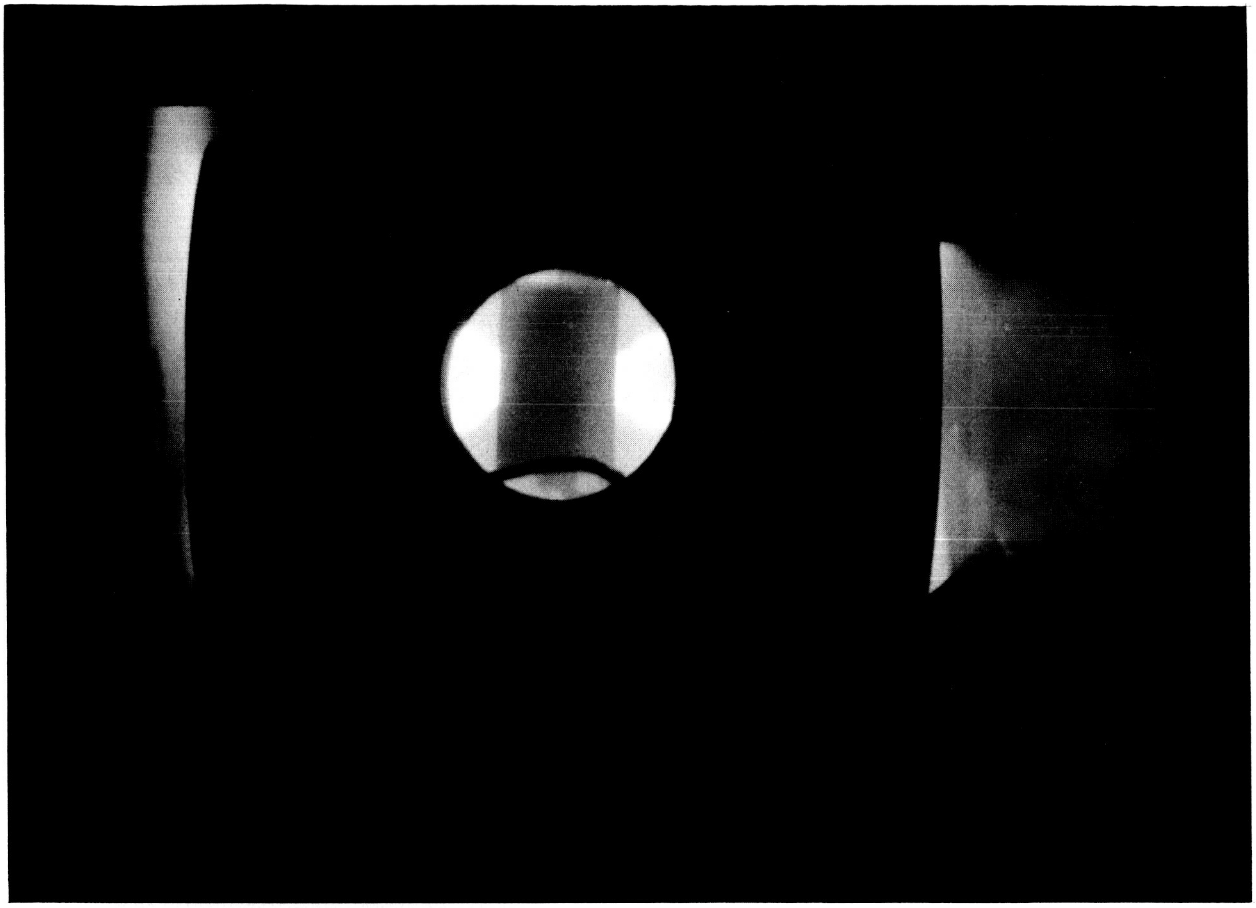

Fig. 2 Operation of the radiation heat transfer apparatus. Luminous ablating material is discharging through the clearance between test specimen and electrodes.

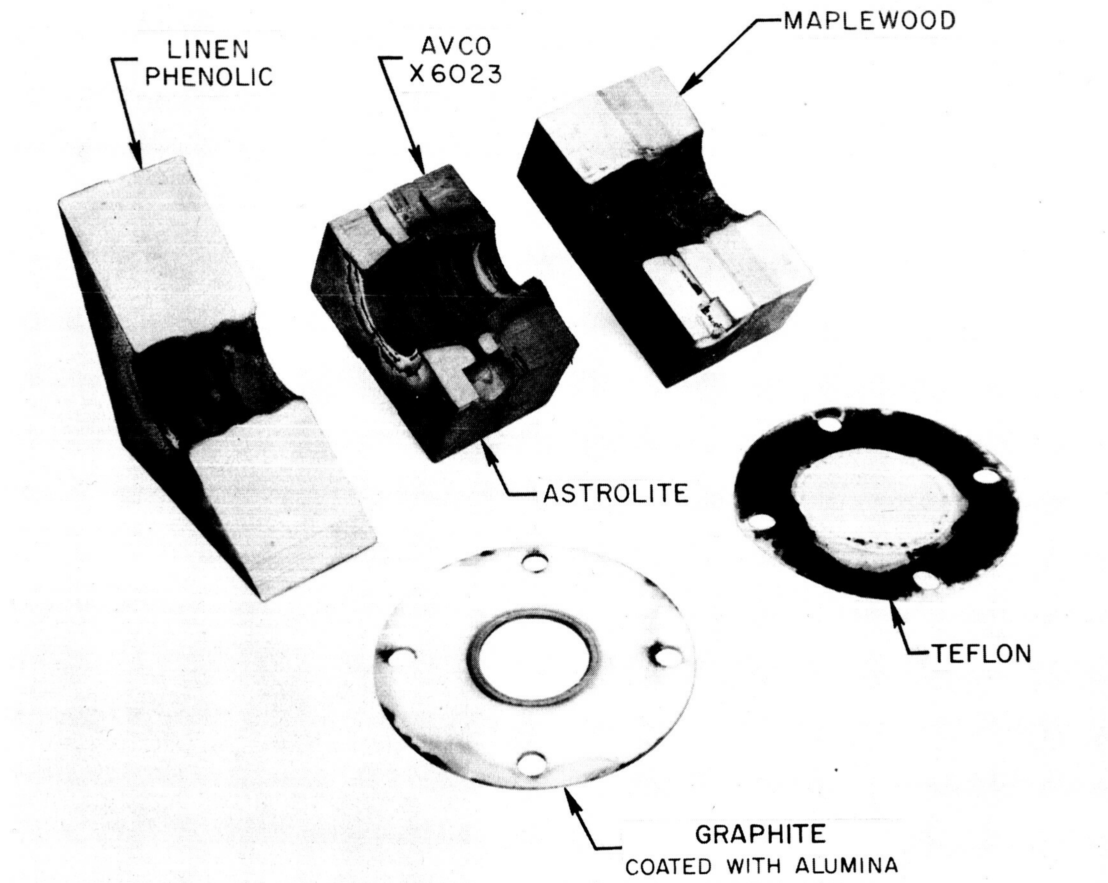

Fig. 3 Representative samples following test

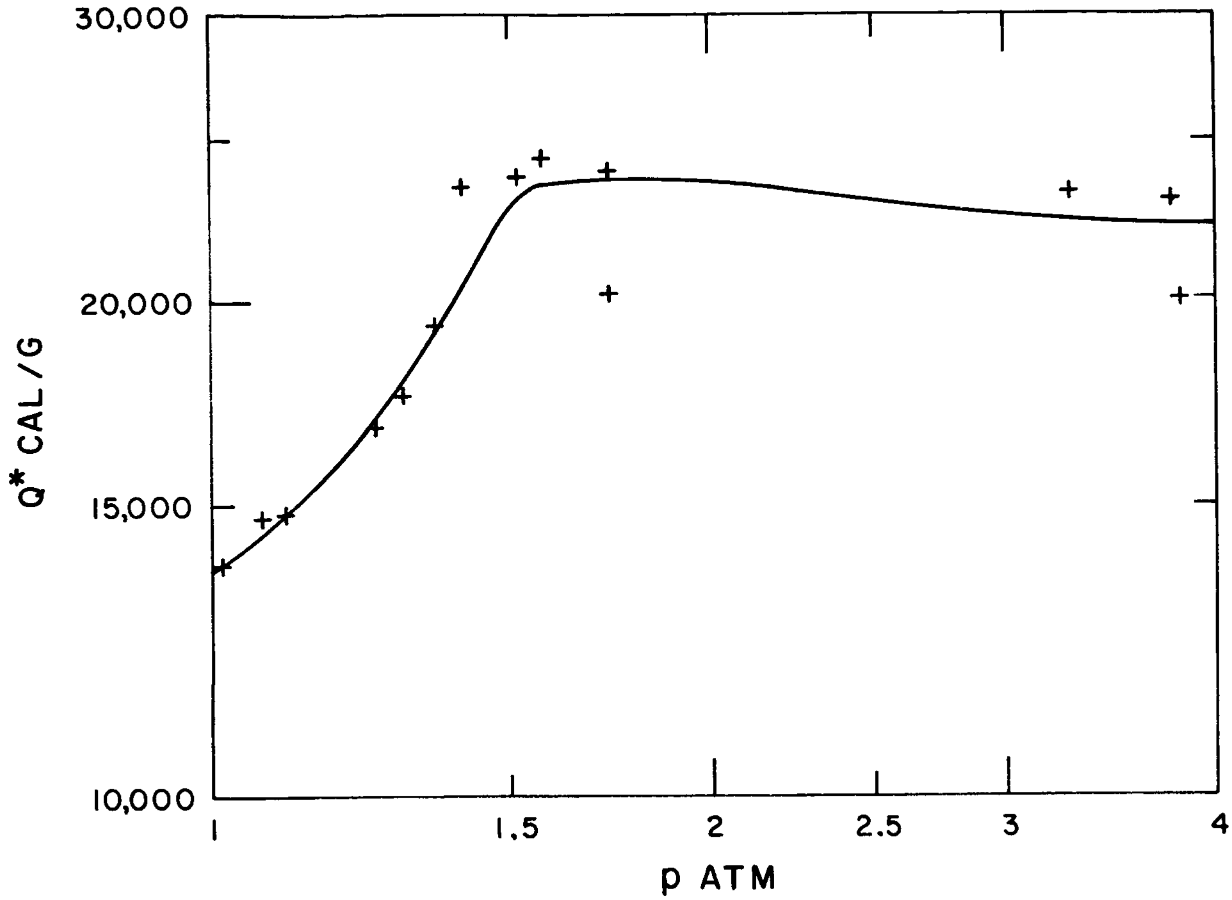

Fig. 4 Measured heat of ablation (Q*) of linen phenolic as a function of pressure

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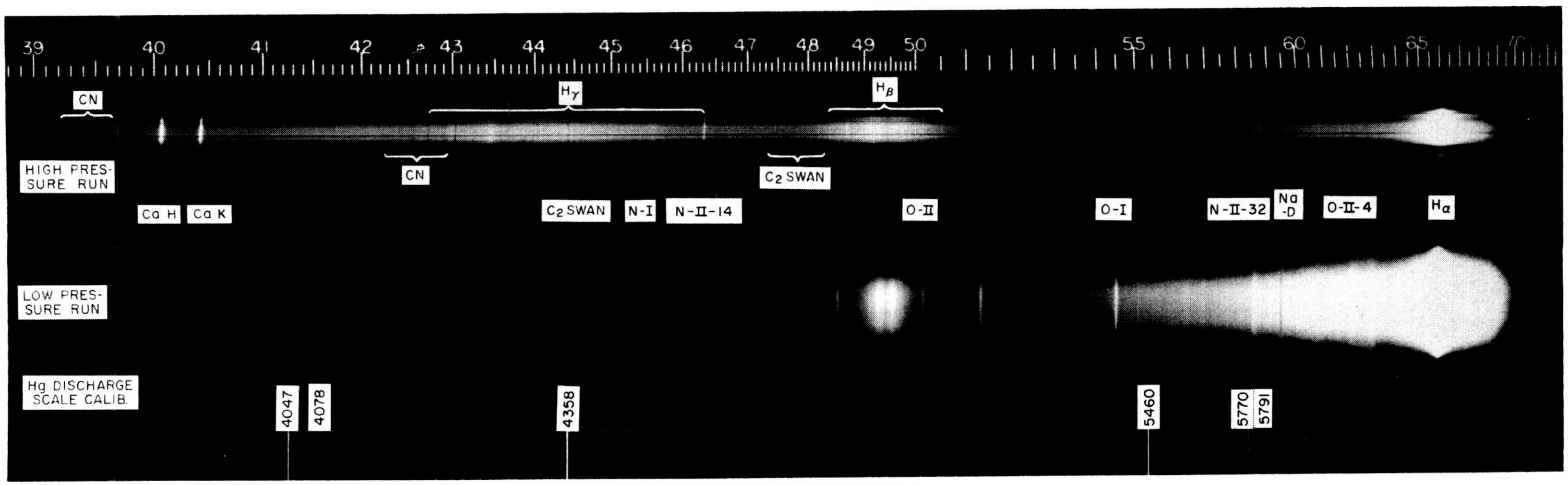

Fig. 5 Radiation spectra of high powered arc at 1.5 atm and 3.78 atm.

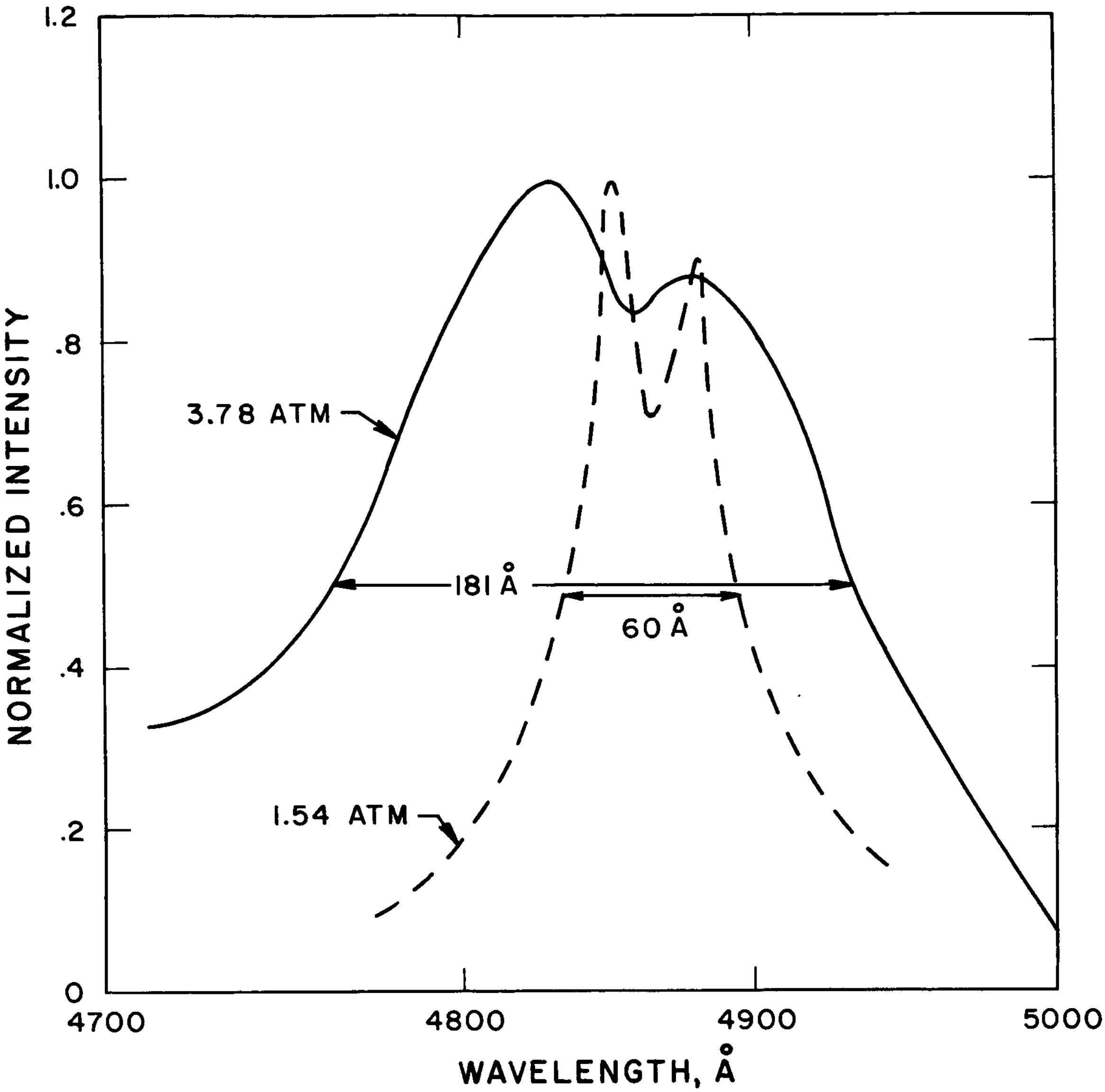

Fig. 6 Broadening of the H_β line.

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